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Some Considerations on the Development of a Core Catcher of a Gas Cooled Fast Reactor

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Abstract

To cover the risks connected to the highly hypothetical accident where the whole or a considerable part of the core is melted down, the use of "core catchers", which can control such core melts, has been suggested. The calculation of the temperature and heat flux distributions in the core melt is very important for the choice of the materials to use for the core catcher.

In this paper the case of a Gas Breeder is being discussed.

Short time transient calculations allow to estimate the temperature at the boundary between core catcher and melt. With the assumptions made in the paper this temperature is 1385 °K for a graphite catcher and 1470 °K for a steel catcher respectively.

The relatively slow instationary processes produced by the decay heat are considered as quasi-stationary and temperature distributions are calculated for various power densities.

For the calculation of the stationary temperature and heat flux distributions, we assume that the natural convection is fully established and that solid and liquid layers are formed according to the temperature profile. The convection in the layer with natural convection is given by many little vortices (Bernard cells). For such a configuration the temperature differences of the boundary layers can be calculated with the relationship of Fiedler and Wille:

$$Nu = 0.177 \cdot Ra^{0.295}$$

The results of the calculations show that, due to the formation of two layers of oxide fuel, one solid and one of stagnant liquid respectively, only a little portion of the decay heat can be absorbed by the core catcher.

Furthermore, in the paper the possibility of using graphite as core catcher constituent material is dealt with.

Two type of emergency cooling are investigated: the so called dry cooling, without the introduction of a supplementary coolant, and the wet cooling, with the introduction of a supplementary liquid coolant, such as for istance a molten salt.

Überlegungen zur Entwicklung eines Core Catchers für einen gasgekühlten schnellen Reaktor

Zusammenfassung

Wird der Kern eines Reaktors ungenügend gekühlt, so kann dies zu seinem Niederschmelzen führen. Um auch die mit einem solchen hypothetischen Unfall vorhandenen Restrisiken abzudecken, untersucht man auch, wie eine solche geschmolzene Kernmasse in einem "Core Catcher" bewältigt werden kann. Für die Beurteilung der Verwendbarkeit bestimmter Auffangwannenmaterialien ist von entscheidender Bedeutung die Temperaturverteilung und die Wärmeflüsse, die in der niedergeschmolzenen Coremasse auftreten. Auf die möglichen Verhältnisse bei einem gasgekühlten Brüter wird eingegangen, wobei zunächst die kurzzeitigen transienten Vorgänge diskutiert und die Temperatur an der Grenzfläche Core Catcher und Schmelze berechnet werden. Sie erreicht unter den gemachten Annahmen bei einem Core Catcher aus Graphit 1385°K und bei einem aus Stahl 1470°K.

Die langzeitlichen instationären Vorgänge, die durch Abklingen der Nachwärme verursacht werden, werden quasistationär behandelt und die Temperaturprofile für verschiedene Leistungsdichten berechnet.

Zur Berechnung der stationären Temperatur- und Wärmeflußverteilung wird angenommen, daß die Naturkonvektion in der flüssigen Schmelze voll angelaufen ist und, daß entsprechend des eingestellten Temperaturprofils feste und flüssige Schichten existieren.

Die Konvektion in der Schicht mit Naturkonvektion besteht aus vielen kleinen Wirbeln (Bernard-Zellen). Für eine solche Strömung können die Temperaturdifferenzen der Schichtgrenzen nach Fiedler und Wille mit folgender Beziehung ermittelt werden

$$Nu = 0.177 \cdot Ra^{0.295}$$

Aus den Ergebnissen der durchgeführten Rechnungen ist zu entnehmen, daß durch die Ausbildung einer festen bzw. stagnierenden Schicht des oxidischen Brennstoffs nur ein geringer Teil der Nachwärme durch den Core Catcher abgeführt wird.

In diesem Bericht wird weiterhin auf die Verwendung von Graphit als Core Catcher-Material eingegangen. Neben der sog. Trockenkühlung, bei der kein zusätzliches Kühlmittel verwendet wird, wird die Naßkühlung, d.h. mit einem flüssigen Kühlmedium, diskutiert. Bei den flüssigen Kühlmitteln werden auch die geschmolzenen Salze in Betracht gezogen.

1. Basic Problems

If the core of the reactor is cooled insufficiently, this may result in its melt down. If there is no suitable device for catching this molten core, a so called core catcher, the molten core may be released into the open air, as a consequence of breaching of the pressure and safety containments. So far accidents resulting in core melt down were regarded in the considerations of reactor design as being so unlikely as not to be considered as a design base accident. In order to protect ourselves also against the residual risks connected with the hypothetical accidents of this type, initial steps have been taken recently with the purpose of including this accident possibility in the considerations as well.

A differentiated assessment of reactors operated with different coolants shows that the dynamical processes which may result in melt down accidents differ greatly. Thus it shows in the water and liquid metal cooled reactors that emergency cooling would delay the process of melt down, but that on the other hand the hazard of a chemical reaction, such as metal-water or of a thermal explosion fuel-sodium, would give rise to new problems. These additional problems, that is to say reactions between the core materials and the coolant, will not arise in a gas cooled reactor.

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2. Situation in the Molten Core Collected in a Flat Catching Pan

As a consequence of the low thermal capacity and the bad thermal conductivity of the coolant there will be no fragmentation of the molten core and no formation of granules in a gas cooled breeder. This even applies to the case of a molten core dripping away, which also gives rise to a continuous melt on the bottom. The low heat removal on the top of this layer and the small thermal critical thickness of the layer of oxide fuel, with bad thermal conductivity and all of the volume heated, result in a rapid distribution of a melt over the bottom of the core catcher. This prevents the formation of a critical mass and consequently a nuclear excursion. In the most adverse case a melt-down in the core catcher will have to be anticipated in a gas breeder after termination of the incident, this melt being close to its boiling point.

Experiments conducted by Fischer and others /1/ have shown that oxide fuel and structural metal are always separate, not only during the melt down phase but also in the core catcher, which means a two layer arrangement in the core catcher. Accordingly the fission products are distributed in these two layers in accordance with their chemical behaviour, which corresponds to a break down of decay heat of 5o % in the oxide, 3o % in the metal phase and 2o % of the decay heat in the gas space.

3. Temperature and Heat Flux Distribution in the Melt

These considerations are based on a flat catching pan with a level bottom as the core catcher (fig. 1) over which the molten fuel is spread with a constant thickness. For studies of the temperature and heat flux distributions in the melt the problem was broken down into three areas:

a) Short Time Transient Events (< 2o sec)

Here studies are limited to the events shortly after the entering of a melt at a temperature of approximately 35oo$^{\circ}$K into a core catcher. In this case the following simplifying assumptions may be made with a good approximation.

- The melt and the bottom of the crucible are regarded as infinite half-spaces each.
- The temperature in the melt and at the bottom of the crucible is assumed to be constant over the entire half-space at the time $t = o$ and is of the magnitude T_1 and T_2 respectively.
- Zone 1, melt, and zone 2, crucible, contain no heat sources. This simplifying assumption holds true for short time effects, as has been shown by the preliminary results achieved in numerical calculations of the non-steady state longtime problem, in which volume heat sources in the melt were taken into account.

Under these assumptions according to Carslaw and Jaeger /2/ and Epstein /3/ exact solutions can be indicated for the non-steady state temperature field taking into account possible phase transitions in the melt, liquid to solid, and in the crucible, solid to liquid.

In the special case of the molten fuel solidifying from the contact area between the melt and the crucible onward, without affecting the crucible, the following relation is found for the contact area temperature:

$$T_i = T_2 + \frac{T_{1,MP} - T_2}{1 + \sigma \cdot \mathrm{erf}\ \lambda_1}$$

where the solidification constant λ_1 can be found by solving the following transcendental equation:

$$\frac{\sigma}{(1+\sigma \cdot \mathrm{erf}\ \lambda_1)\ \exp\ (\lambda_1^2)} - \frac{\theta}{\mathrm{erfc}\ (\lambda_1\ \beta_1)\ \exp\ (\gamma_1\ \lambda_1^2)} = \lambda_1 \cdot \Lambda$$

where

T_i = temperature of the interface

T_1 = constant temperature of the melt at the time $t = o$

T_2 = constant temperature of the crucible at the time $t = o$

$T_{1,MP}$ = melting temperature of the molten core

$\alpha_{i,j}$ $= \dfrac{K_{i,j}}{c_{i,j} \cdot \rho_{i,j}}$ = thermal diffusivity

i = zone index (1 being the molten core; 2 being the crucible)

j = phase index (s being solid, m being molten)

k = thermal conductivity

c = specific heat

ρ = density

$$\sigma = \left(\frac{\alpha_{1,s}}{\alpha_{2,s}}\right)^{1/2} \frac{K_{2,s}}{K_{1,s}}$$

$$\gamma_1 = \frac{\alpha_{1,s}}{\alpha_{1,m}} = \beta_1^2$$

$$\theta = \beta \frac{K_{1,m}}{K_{1,s}} \left(\frac{T_1 - T_{1,MP}}{T_{1,MP} - T_2} \right)$$

$$\Lambda = \frac{L_1 \cdot \pi^{1/2}}{c_{1,s} (T_{1,MP} - T_2)}$$

L_1 = fusion heat of the molten core

For a temperature of the melt of T_1 = 35oo°K which is approximately the boiling point of the fuel, and a uniform initial temperature of 5oo°K of the crucible, with steel and graphite respectively as the crucible material, one obtains

T_i = 147o°K for steel

T_i = 1385°K for graphite.

These results, and the results indicated in fig. 2 for steel and graphite as crucible materials, show that as a consequence of the major difference in temperature conductivity in oxide fuel and in the crucible material, the interface temperature, fuel to crucible, is low and that a layer of solid fuel is generated rather quickly.

b) Steady State Temperature and Heat Flux Distributions

Models according to /4/ and /5/ can be used to calculate the steady state temperature and heat flux distributions. In the integral consideration /4/

it is assumed that natural convection has been fully started in the liquid melt and that a steady state temperature distribution has been formed. Calculation of the temperature distribution is based on a model in which a solidified layer of fuel at the bottom of the core catcher, cooled from below, is followed by a stagnant liquid fuel layer, at the top of which the maximum temperature of the melt is reached. This line of maximum temperature at the same time represents the separation line of the heat flux. On top of this layer there is another layer of molten fuel in which the heat is transported by natural convection. This convection consists of a large number of small vortices constituting a hexagonal flow pattern (Benard-Cell). For a flow of this type, the temperature differences of the boundary layers can be determined according to Fiedler and Wille /6/ by means of the following relation:

$$Nu = o.177 \cdot Ra^{o.295}$$

In this model it is assumed moreover that the fuel layer is followed by the liquid molten steel layer, the top of which is solidified as a function of the magnitude of the decay heat. The heat is fransferred to the environment from this surface by radiation and by a boiling medium respectively. The result of these calculations are plotted in fig. 3 to 6 for various power densities for a heat removal by radiation. The temperature distribution found if a boiling medium is used, in this case $ZnCl_2$, is shown in fig. 7. If natural convection is present in the melt, most of the heat is transferred to the top. If the wall thickness of the bottom of the core catcher pan is selected correctly the temperature at the top of the pan can be kept below 1ooo°K. Presently the results achieved with the model described above are compared with the values calculated with the model by Peckover /5/.

c) Longtime Non-Steady State Processes

If the pan is made of the right material and the right thickness, it will not start melting down. In this case the longtime non steady state events caused by the decay of after heat can be dealt with in a quasi-steady state mode. In this case the temperature profile was calculated at various power densities (see fig. 4).

4. Concepts of Cooling the Melt and Materials Problems

As is evident from fig. 6 most of the decay heat must be removed from the surface of the molten core. Only approximately 1/7th of the total decay heat will flow through the bottom of the crucible.

4.1 Cooling of the Bottom of the Crucible (As Explained by the Example of the Graphite Crucible)

Because of the excellent thermal conductivity of graphite, cooling of the crucible in this case does not entail any major difficulties, because the heat transferring surface of the cooling pipes can be made large by staggering in depth, as it is shwon for instance in fig. 9 . This concept would have the additional advantage of making also the layer of the pan located underneath the cooling pipes available as a heat sink, which would be very effective in a material of such good heat conducting properties as graphite. In such a concept therefore the core catcher pan would constitute a heat buffer, which would allow starting - up cooling of the pan only after an incident had already occured. Water cooling would require a minimum flow of water of approximately 5o l/s with a heating range of approximately 4o°C. The use of helium as a coolant would be another possibility in this case, because of staggering of the cooling pipes in depth.

4.2 Cooling of the Surface of the Melt

In principle it is possible to remove the heat from the surface of the molten down core either without introducing an additional coolant to the molten core - the so called dry cooling principle - or by adding a liquid coolant, that is by wet cooling.

a) Dry-Cooling

In dry-cooling, heat is removed to a lesser extent by heat removal via the core catcher and to a major extent by heat radiation. This heat radiation would heat the reactor internals to the point of the melting. Accordingly it is necessary to either directly cool these reactor internals or protect them against heat radiation by means of a cover over the melting pan, which, in turn, must be cooled. The interaction of the various materials is limited to the material of the catching pan and the oxide and metal phases respectively. It is precisely this cover which creates the most difficult problems in dry cooling. The fuel dropping down from the core may be piled upon this cover as a solid, for instance as fragments of fuel elements, in such a way, or liquid fuel may solidify to such an extent, as to be unable to get into the pan. Accordingly it would radiate into the reactor cavity at a temperature closely below the melting point. In order to prevent the openings of the pan from being plugged-up by a solidified fuel bridge, these openings must be at least 1 thermal layer wide. If one assumes that the core has molten down after approximately 2oo sec, which corresponds to a volume heat source intensity of approximately q^{III}_{fuel} = 15 W/cm^3, according to fig. 8 the minimum inside diameter of the aperture would have to be 9 cm or more. Since the bottom of the cover may be required to accomodate a heat flux of up to 12o W/cm^2, this would also require the installation of cooling pipes embedded in material of good thermal conductivity and staggered in depth.

No particular difficulties arise in the catching pan under the dry-cooling concept. As is shown by thermodynamic calculations for this case, temperatures both in the non steady state and the steady state conditions at the boundary layer between the pan and the melt do not exceed 1385 and 147o°K for graphite and steel respectively. At these temperatures there will not be any hazard of a reaction between the molten core and the graphite and steel pan respectively.

b) Wet-Cooling

The problems of water injection have been discussed already by Klein and Goetzmann /7/. To reduce the chemical reaction of water with the metal phase of the melt, the density can be reduced by diluting the oxide melt with light oxides, in such a way that the oxide melt is on top of the metal phase. This can avoid further release of hydrogen.

According to more recent considerations the use of a low melting and low boiling salt is capable of avoiding the problems connected with water injection. In this case, the salt may be kept available both as a protective layer at the bottom of the core catcher and as an aerosol with an inert carrier gas in the reactor cavity above the core. Aerosol cooling with salts may be used even under incident conditions for shut-down and emergency cooling of the, as yet, undamaged core. In a former report, cooling of the molten core by means of molten salts has already been considered /8/. Preliminary considerations of the problems associated with molten salt and their choice have been reported in an internal report /9/. In this report the chemical stability, the interaction with the molten core, the physical properties, that is melting point and boiling point, corrosive nature and the chemical behaviour with water were taken into consideration. After a first critical survey zinc chloride was selected as a potential coolant. Although there are still many open questions in this respect, the first thermal calculations with this salt as a coolant will be reported in this study. The data used in these calculations are summarized in table 1. For a comparison with other salts the table also shows the values of sodium chloride and cadmium chloride.

The basic concept of cooling with a low boiling salt is the removal of the decay heat from the molten core by means of the heat of evaporation, and condensation at the heat sinks of the reactor system, that is by a sort of heat pipe effect. It should be indicated that this cooling system is still associated with a number of open problems, and it still requires a more detailed consideration, for instance to ensure the recycling of the coolant, then problems of a fuel-salt reaction, of the hydrolysis of the salt as a consequence of the intentional or unintentional addition of water and others. The temperature conditions in the melt encountered in the case of $ZnCl_2$-cooling, as calculated and represented in fig. 7, are intended to show only the basic aspects. If the heat released in the melt until 5000 sec after an accident is to be removed by evaporating $ZnCl_2$ without recycling of that salt, this would require the use of approximately 225 tonnes of $ZnCl_2$.

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TABLE 1

	Symbol	Dim.	$ZnCl_2$	NaCl	$CdCl_2$
Molecular weight	M	g	136,28	58,45	183,32
Melting point	T_{MP}	°C	318 /11/	801 /11, 13/	568 /11/
Boiling point	T_{BP}	°C	732 /10,11/	1465 /10/	980 /11/
Density	ρ	g/cm^3	2.690 500°C /10/ 2.366 650°C /13/	2,139 /10/ 1.502 /13/ $^{900^\circ C}$	3,389 /11/
Specific heat	c_p	cal/g°C	0.177 (solid)	0.260 (solid) 0,274 (liquid) /10/	
Thermal conductivity	λ	$\frac{cal}{cms^\circ C}$	318°C 7.2×10^{-3} /13/		
Dynamic viscosity	η	$dyns/cm^2 \mathrel{\hat{=}} \frac{g}{scm}$	7.48 360°C 4.75 380°C 3.55 400°C 5.00×10^{-2} 700°C /14/	1.04×10^{-2} 897°C /11/	2.07×10^{-2} 637°C /11/
Kinematic viscosity	$\nu=\frac{\eta}{\rho}$	cm^2/s	1.859×10^{-2} 500/700°C 2.113×10^{-2} 650/700°C		
Surface tension	σ	dyn/cm		106.4 900°C /10/	
Heat of fusion	H_F	cal/g	40.6 /12/ 17.98 /10/	114.5 /10/	39,384 /11/
Heat of vaporisation	$H_{vap.}$	cal/g	210.6 /12/	775.0 /10/	
Heat diffusivity	$a=\frac{\lambda}{c_p\rho}$	cm^2/s	1.512×10^{-2}(500°C)		
Prandtl Number	$Pr=\frac{\nu}{a}$		1.23		

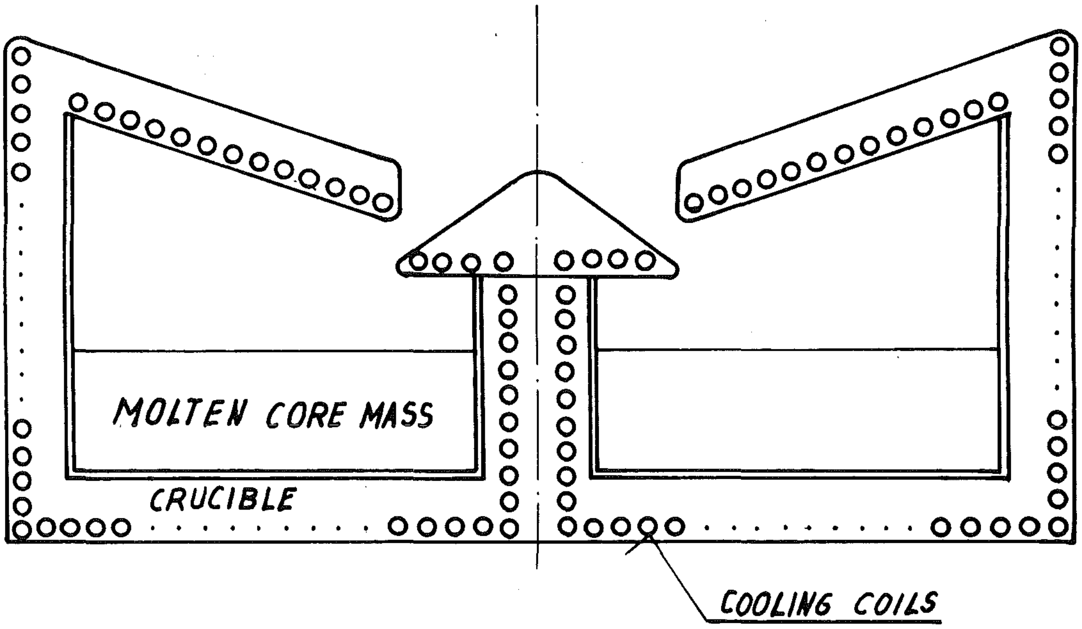

Fig. 1 Core catcher concept for a GCFR.
Schematic outline

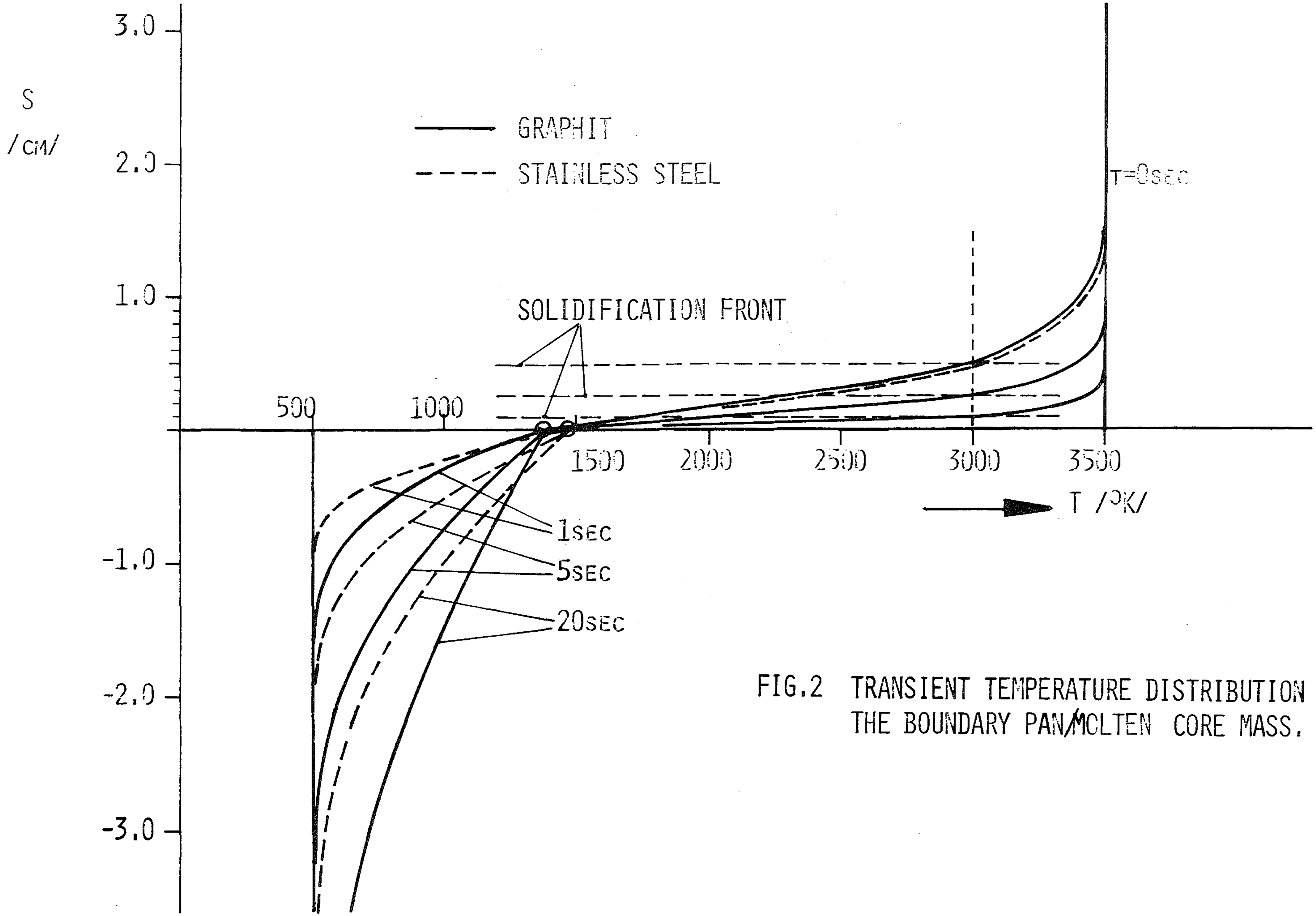

FIG.2 TRANSIENT TEMPERATURE DISTRIBUTION ON THE BOUNDARY PAN/MOLTEN CORE MASS.

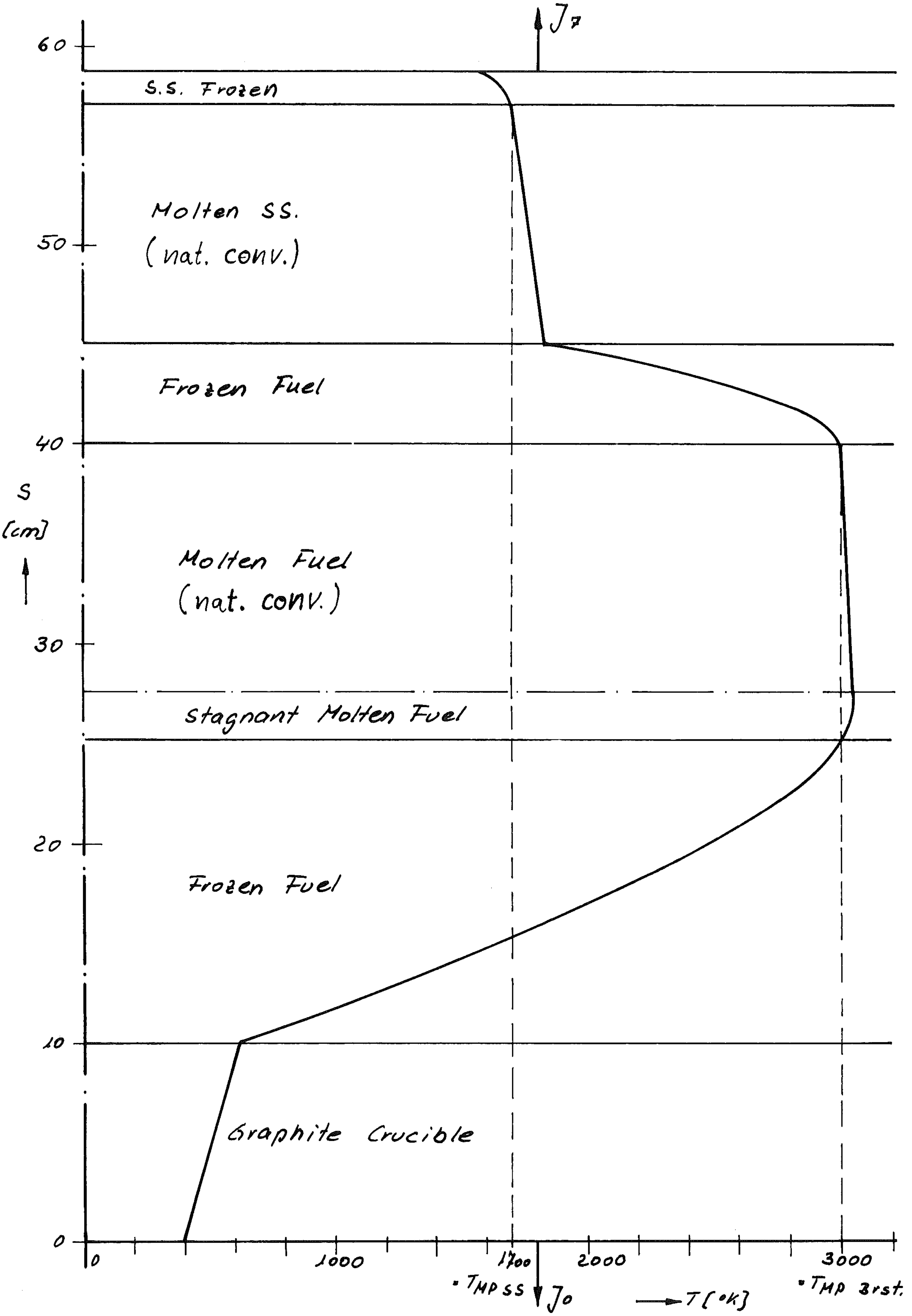

Fig. 3 Temperature profile in the core melt
Total decay heat : 15 MW

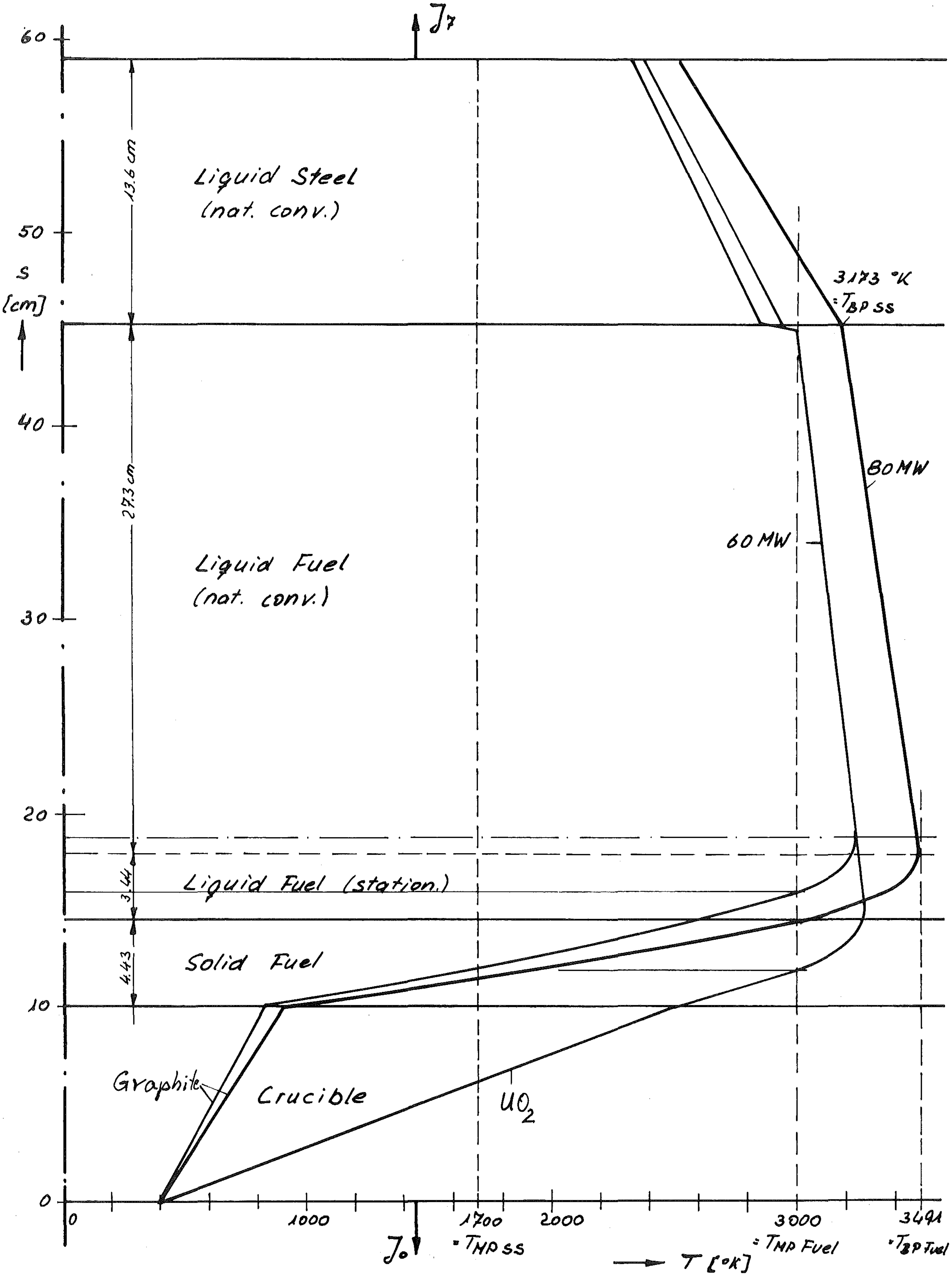

Fig. 4 Temperature profile in the core melt.
Decay heat : 60 and 80 MW

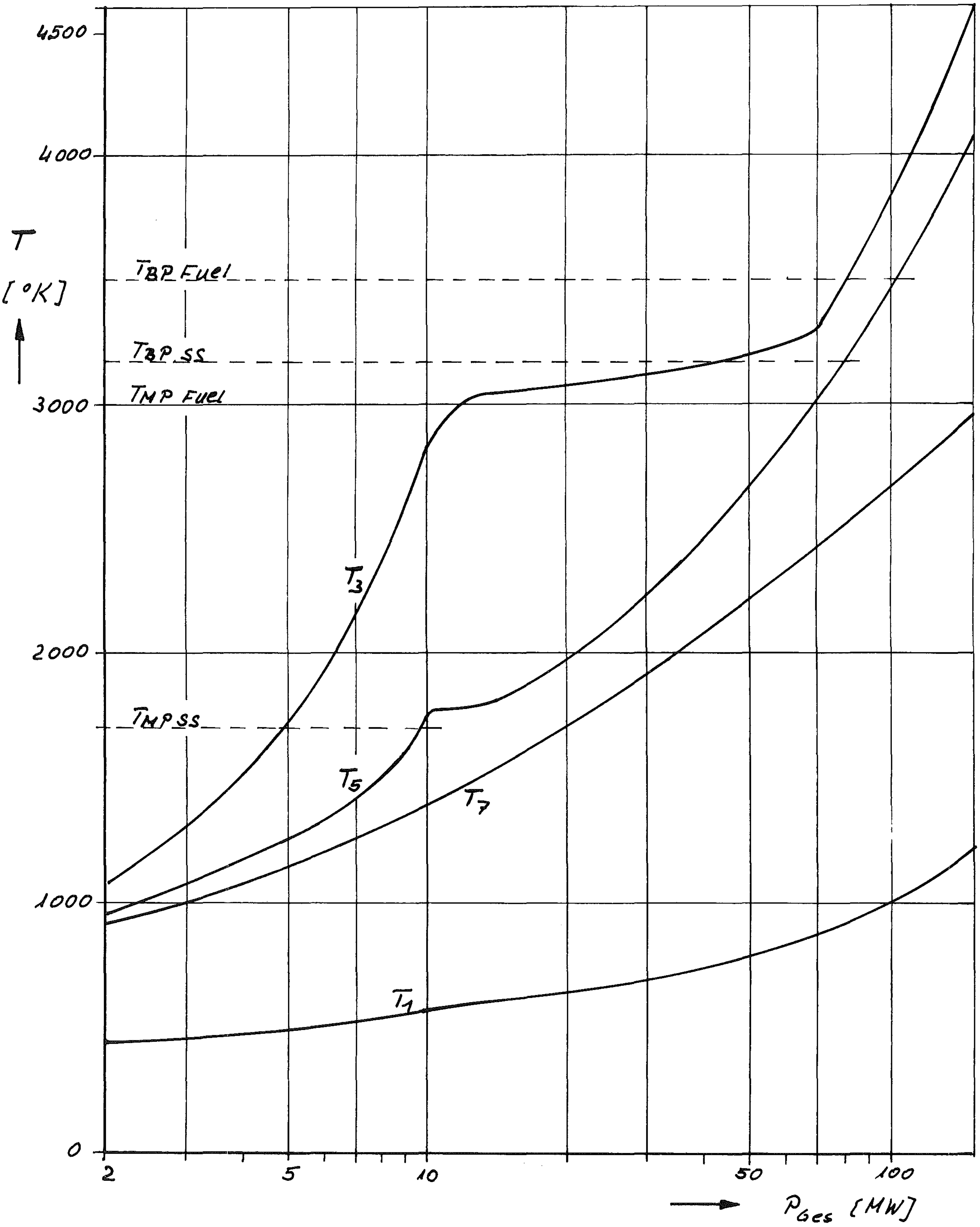

Fig. 5 Relation between total decay heat and temperature in the core catcher.

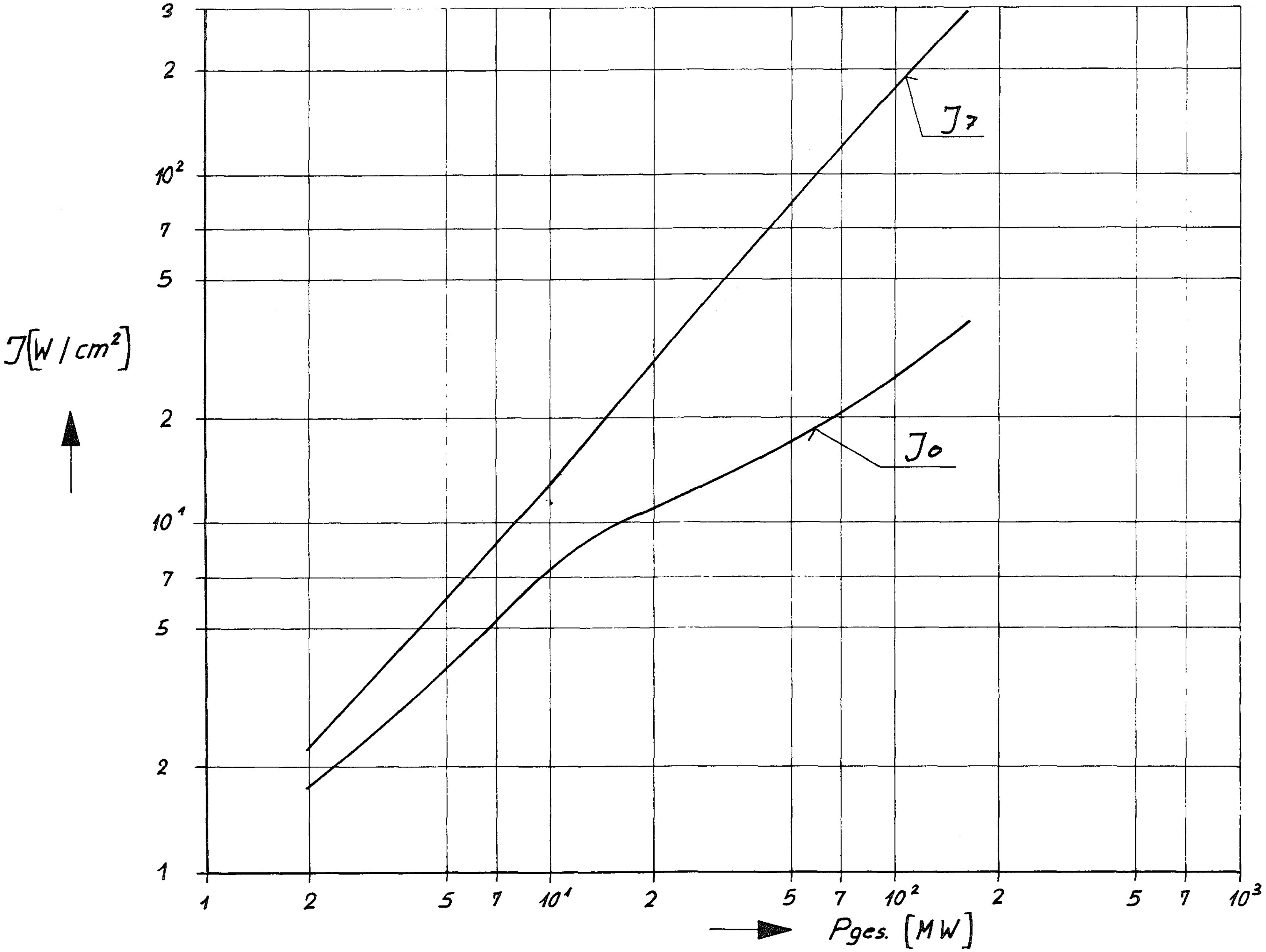

Fig. 6 Relation between heat-fluxes and total decay heat in the core catcher

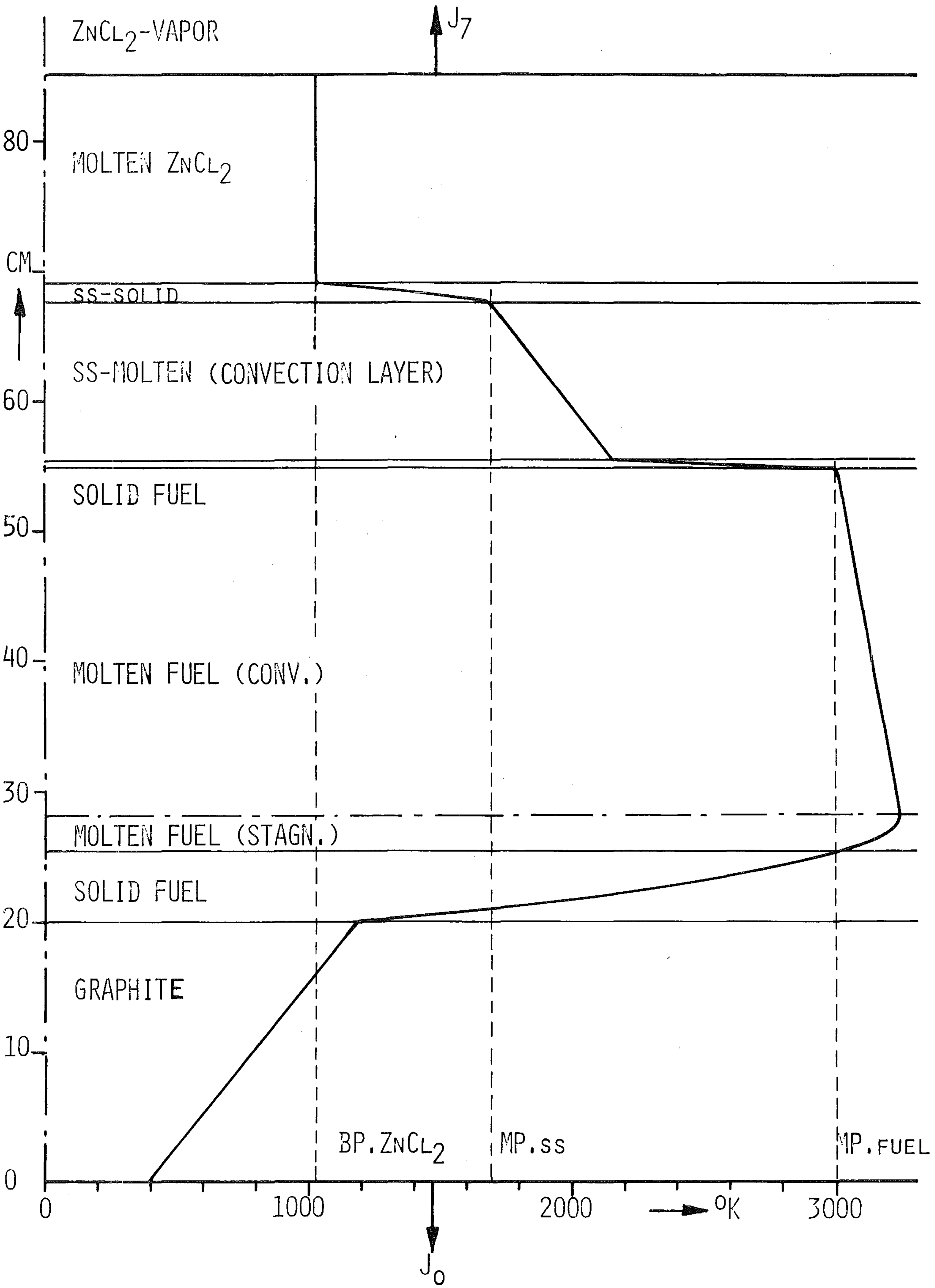

FIG.7 HEATFLUX AND TEMPERATURE DISTRIBUTION IN A MOLTEN CORE MASS WITH GRAPHITE CORE CATCHER AND MOLTEN $ZnCl_2$ AS A BOILING HEAT TRANSFER MEDIUM. TOTAL DECAY HEAT: 60 MW

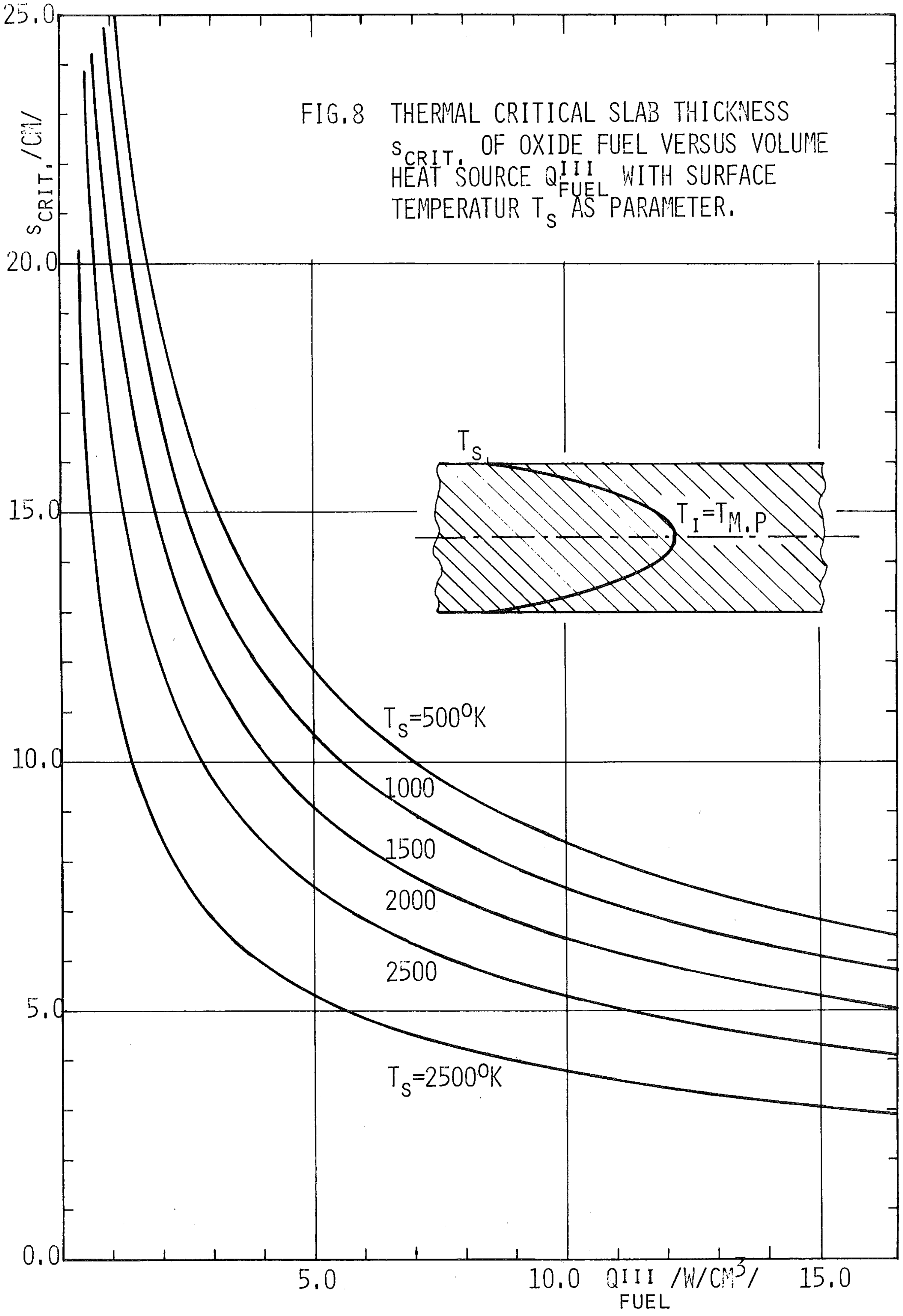
FIG.8 THERMAL CRITICAL SLAB THICKNESS $s_{CRIT.}$ OF OXIDE FUEL VERSUS VOLUME HEAT SOURCE Q^{III}_{FUEL} WITH SURFACE TEMPERATUR T_S AS PARAMETER.

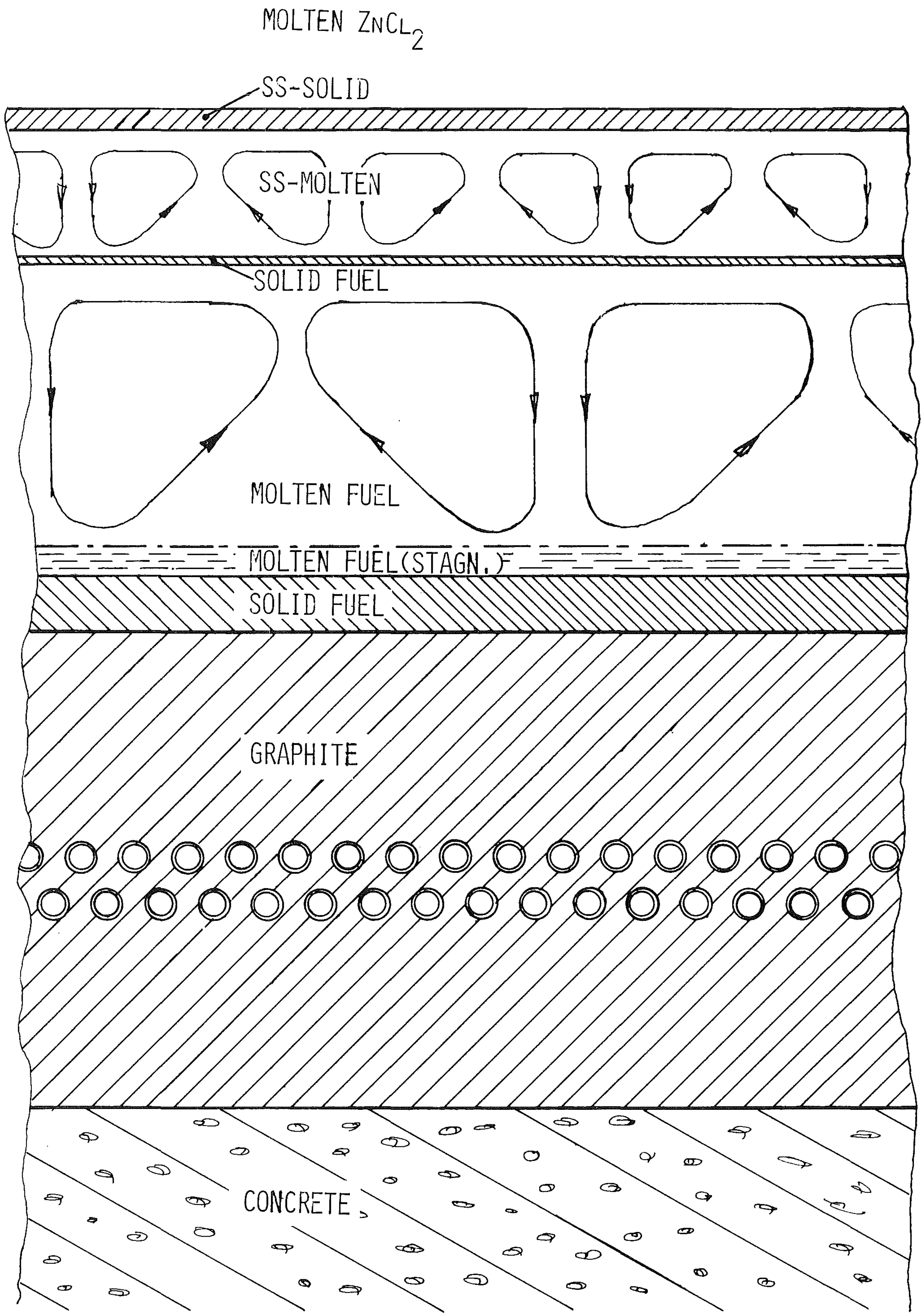

FIG. 9 SCHEMATIC OUTLINE OF THE CONDITIONS IN A FLAT PAN CONCEPT WITH STAGGERED COOLING PIPES.